# CAM-SE: CAM with HOMME's Spectral Element Dynamical Core

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SEOM: Iskandarani, Haidvogel

SEAM: Fournier, Taylor, Tribbia, Wang

HOMME: Dennis, Edwards, Erath, Evans, Guba, Levy, Loft, Nair, Norman, St-Cyr, Taylor, Thomas

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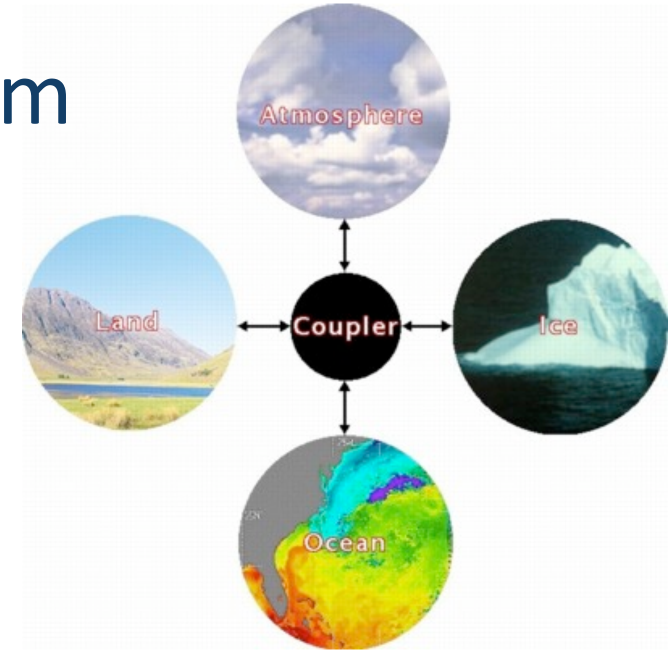
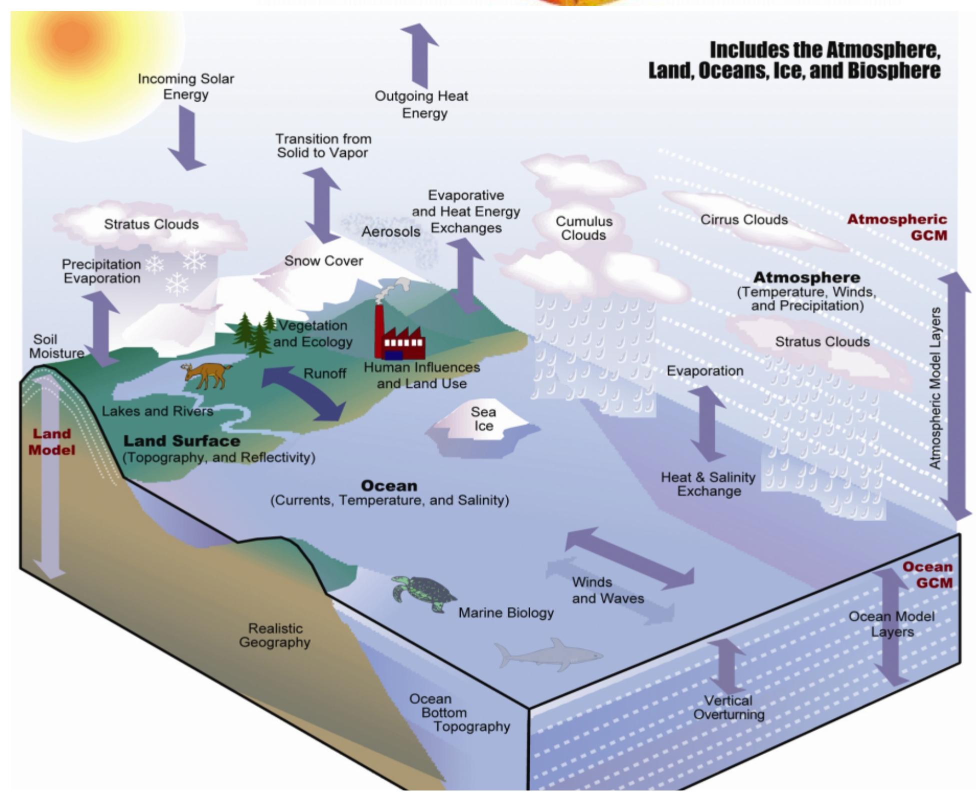
U.S. Department of Energy

Office of Science

# The Community Earth System Model (CESM)




- CAM is the atmosphere component model for the CESM
- CESM is an IPCC-class model developed by NCAR, National Labs and Universities
- Atmosphere, Land, Ocean and Sea ice component models
- Science & policy applications:
  - Seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
  - Contribute to assessments

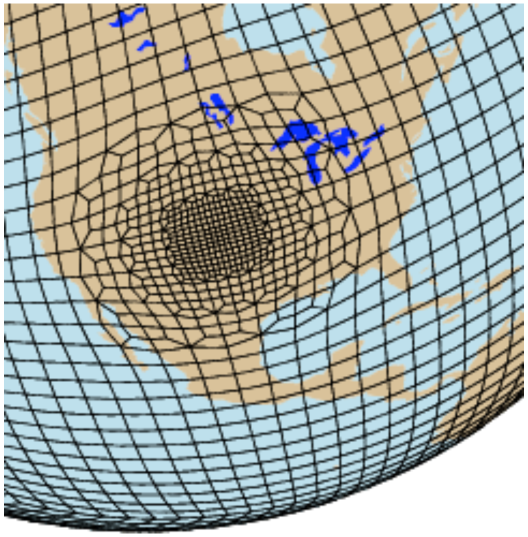


# CAM Dycore Options

- CAM-EUL
  - Used in IPCC AR4
  - Global spectral model
  - Eulerian dynamics, Semi-Lagrangian tracer advection
- CAM-SLD
  - Global spectral model
  - Semi-Lagrangian tracer and momentum advection
- CAM-FV
  - Current default core, used in IPCC AR5
  - Lin-Rood lat/lon FV
- CAM-SE
  - New option included since CAM 5.0 release
  - Spectral element dynamical core from HOMME

# HOMME

- HOMME: High-Order Method Modeling Environment
  - Runs in CAM or stand-alone
  - Quadrilateral grids (cubed-sphere or conforming unstructured)
  - CG (continuous Galerkin, aka spectral elements) and DG (discontinuous Galerkin) methods
  - CSLAM advection

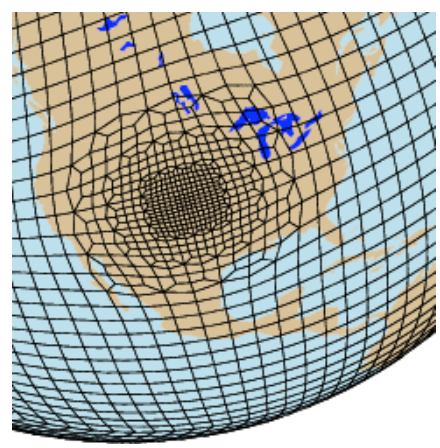


# Design Philosophy (original)

- Scalable, drop-in replacement for CAM's global spectral method
- Spectral element horizontal discretization replaces spherical harmonic expansion
- All other aspects followed CAM-EUL
  - log(ps) prognostic variable (no mass or energy conservation)
  - S&B MWR 1981 vertical coordinate (Lorenz staggering, eta coordinate)
  - Run at 8'th order accuracy (p=7 element, polynomial basis functions (like spherical harmonics, which are polynomials in $R^3$ restricted to the sphere)
  - Hyper-viscosity applied to momentum and temperature ( nu ~ dx^3.2)
  - Top-of-model (3 levels) regular viscosity, fixed coefficient

# Design Philosophy (revisionist)

- Support quasi-uniform and variable resolution grids on parallel computers
  - Finite Element Method (designed from inception for these types of grids)
  - Derivatives are computed locally within each element – independent of neighbors/connectivity
  - Galerkin formulation allows for mathematical proofs of convergence rates on highly unstructured grids
  - Galerkin formulation leads to natural cache friendly design



# Design Philosophy (revisionist)

- Use explicit time integration
  - Require diagonal mass matrix:  use  CG/"spectral elements" or DG
- Hyper-viscosity for physical diffusion
  - Simple and effective "turbulence" model
  - CG:  Efficient doubly-integrated-by-parts formulation
  - DG:  more difficult (still a research topic) but can use flux limiters
- Diagonal mass matrix CG:  requires quadrilateral elements (not triangles)

# Design Philosophy (revisionist)

- Hyper-viscosity damps grid scale waves (2dx-6dx)
  - Not afraid of "erratic" grid scale waves (Melvin et. al QJRMS 2012)
  - $Q^p$-$Q^p$ element with all variables in the same functional space (would require FE stabilization if not using hyper-viscosity)
  - Similar to high-order A-grid, with waves $\lambda > 2\pi h/(2p+1)$ very well resolved (Ainsworth & Wajid SINUM 2009)

# Design Philosophy (revisionist)

- $Q^p$-$Q^p$ element is *mimetic*
  - Discretization preserves adjoint properties of div, grad and curl operators
  - Discrete versions (element level) of Stokes and Divergence theorem
  - Conservation: exact local conservation: mass, potential temperature, 2D PV.
  - Conservation (exact with exact time integration) total energy.

# Design Philosophy (revisionist)

- $Q^7$-$Q^7$   8'th order accurate element
  - In test cases, outperforms lower order elements with same total number of degrees of freedom, even for problems like advecting the slotted cylinder
  - *8$^{th}$* order convergence obtainable (but with unrealistic timesteps and diffusion coefficients)
  - Small timestep because of Gauss-Lobatto quadrature spacing
- $Q^1$-$Q^1$   2$^{nd}$ order accurate element
  - Quadrature used to obtain a diagonal mass matrix is too inaccurate
- $Q^3$-$Q^3$   4$^{th}$ order accurate element
  - Compromise typically used in CAM

# Tracer Advection Example

- $Q^3$-$Q^3$ element, unlimited, is 4'th order accurate, oscillatory
- Mimetic spectral elements and DG methods can use element-local, monotone reconstructions (2'nd order accurate)
- Current work in HOMME: CSLAM semi-Lagrangian advection option for tracers.

# Nari & Lauritzen Deformational Flow Test Case for the sphere

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